Doherty & Pratt

The Comparison of Gas Engines And Steam Turbines as Prime Movers, and the Design Of a Six Hundred Kilowatt Steam Turbine Plant

Electrical Engineering

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THE COMPARISON OF GAS ENGINES AND STEAM TURBINES AS PRIME MOVERS, AND THE DESIGN OF A SIX HUNDRED KILOWATT STEAM TURBINE PLANT

BY

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FRED CAMERON PRATT

THESIS FOR THE DEGREE OF BACHELOR OF SCIENCE

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IN THE

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UNIVERSITY OF ILLINOIS

June 1, 1909

THIS IS TO CERTIFY THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

ROBERT ERNEST DOHERTY and FRED CAMERON PRATT

ENTITLED THE COMPARISON OF GAS ENGINES AND STEAM TURBINES AS PRIME MOVERS, AND THE DESIGN OF A SIX HUNDRED KILOWATT STEAM TURBINE PLANT

IS APPROVED BY ME AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE

DEGREE OF Bachelor of Science in Electrical Engineering

Edwd. H. Waldo
Instructor in Charge

APPROVED: Morgan Brooks.

HEAD OF DEPARTMENT OF Electrical Engineering

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INTRODUCTION

The object of this thesis is to design a power plant that will fulfill the lighting and power requirements of the University of Illinois, with a consideration of only gas engines and steam turbines as prime movers. The lighting and power requirements of the University were taken in order that the design might be limited to actual conditions.

INVESTIGATION OF PRESENT AND FUTURE CONDITIONS.

In order to find out just what the present power requirements of the University are, a set of daily switchboard logs covering one year's time (from May 1908 to May 1909) was obtained from the Engineer's office. These log sheets were gone over carefully, and from them four were chosen, which represented the typical conditions of March, June and September. One was chosen from December to represent the maximum output for the year. Load curves were plotted from this data.

It was found from the Physics Department and the Engineer's office that the Physics building will have a possible power intake of eighty kilowatts, and the Administration building, thirty kilowatts. The Y.M.C.A. building is carried at present, but only at times when the power plant is not heavily loaded.

Therefore, the load required by this building at times of peak load should be added to the present peak in estimating the future load. Although under ordinary conditions the maximum demand of the Y.M.C.A. building does not occur at times of peak loads, it is possible on cloudy days for this building to require in the neighborhood of fifteen kilowatts in the morning and afternoon when the plant is most heavily loaded.

The steady increase in laboratory equipment and the enlargement of the Electrical laboratory, which will probably come within the next two years, mean an increased load for the plant. So it is estimated that within two years the plant will have to carry a maximum load of six hundred kilowatts.

This leaves an allowance for an increase of over two hundred kilowatts above the present load. It is remembered,however,that in making a liberal allowance for future power,the load factor is decreased,which means that while the plant is waiting for the increase in load,it will be operating at a comparatively low efficiency.

In view of that fact that in years to come the power requirements of the University may rise above 600 kilowatts, space will be left for the installation of one 250 kilowatt unit.

LOAD CURVES.

A study of the load curves leads to the following conclusions:

(a) At times when school is in session, two sharp peaks occur, one at 10:00 A.M. and one at 3:00 P.M.

(b) When school is not in session, there are no peaks, and the plant runs at a very low load factor.

(c) In no case has the plant been overloaded to any great extent so far as the electrical equipment is concerned.

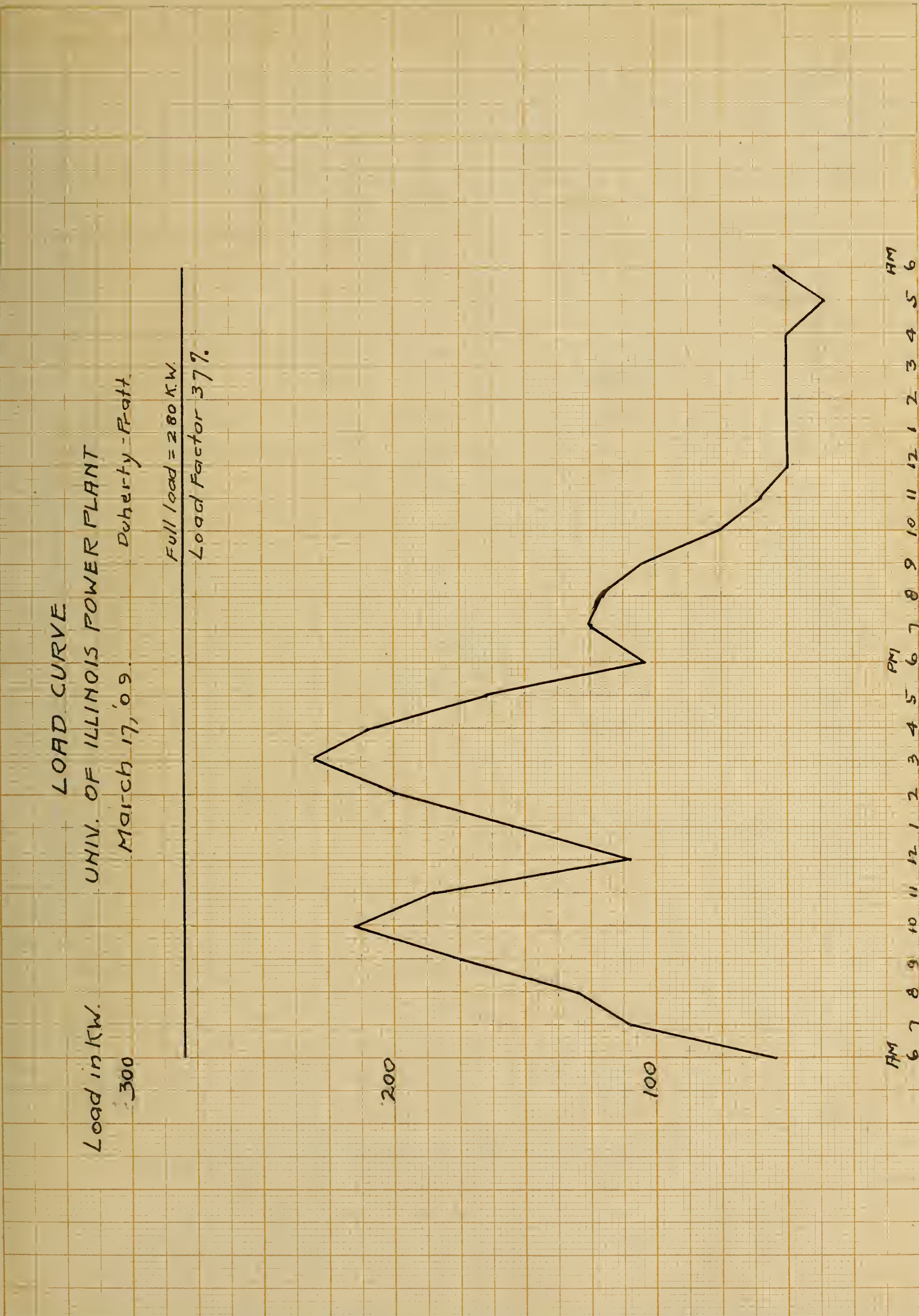
However, the engines are overloaded in the winter on account of the high back pressure, which results from the exhaust steam being used for heating purposes.

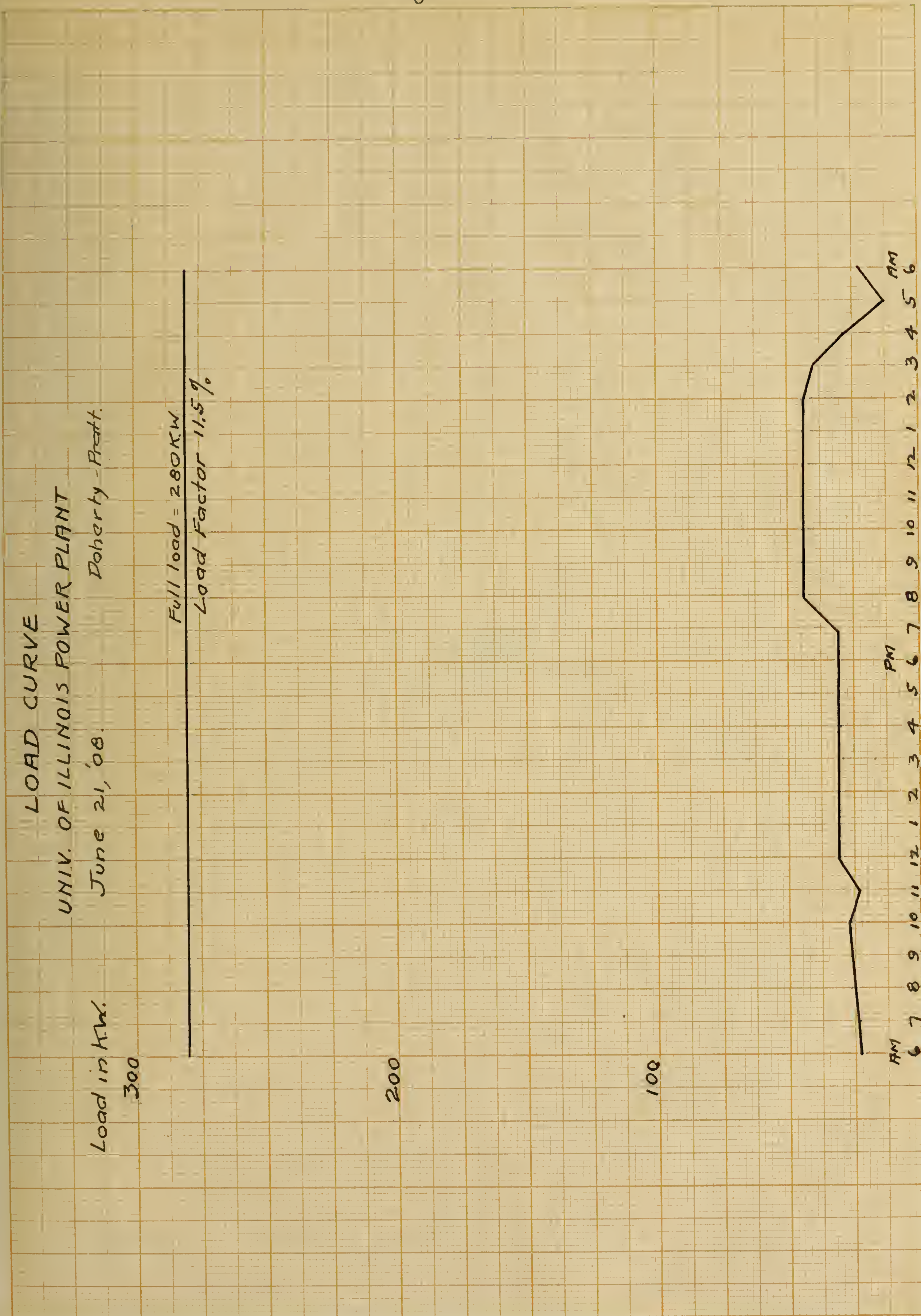
(d) Maximum load two hundred and ninety five kilowatts for one year.

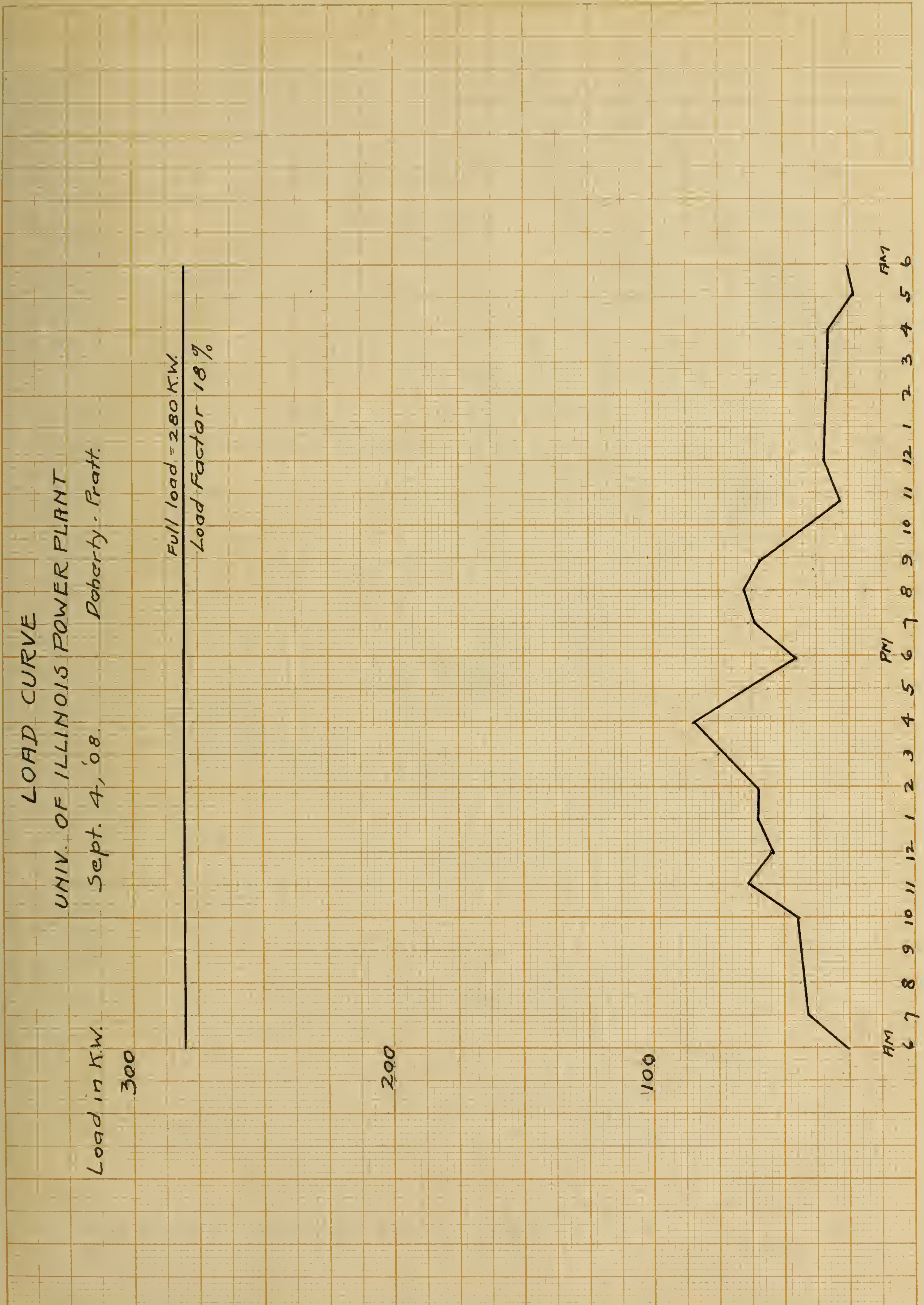
(e) Minimum load twelve kilowatts.

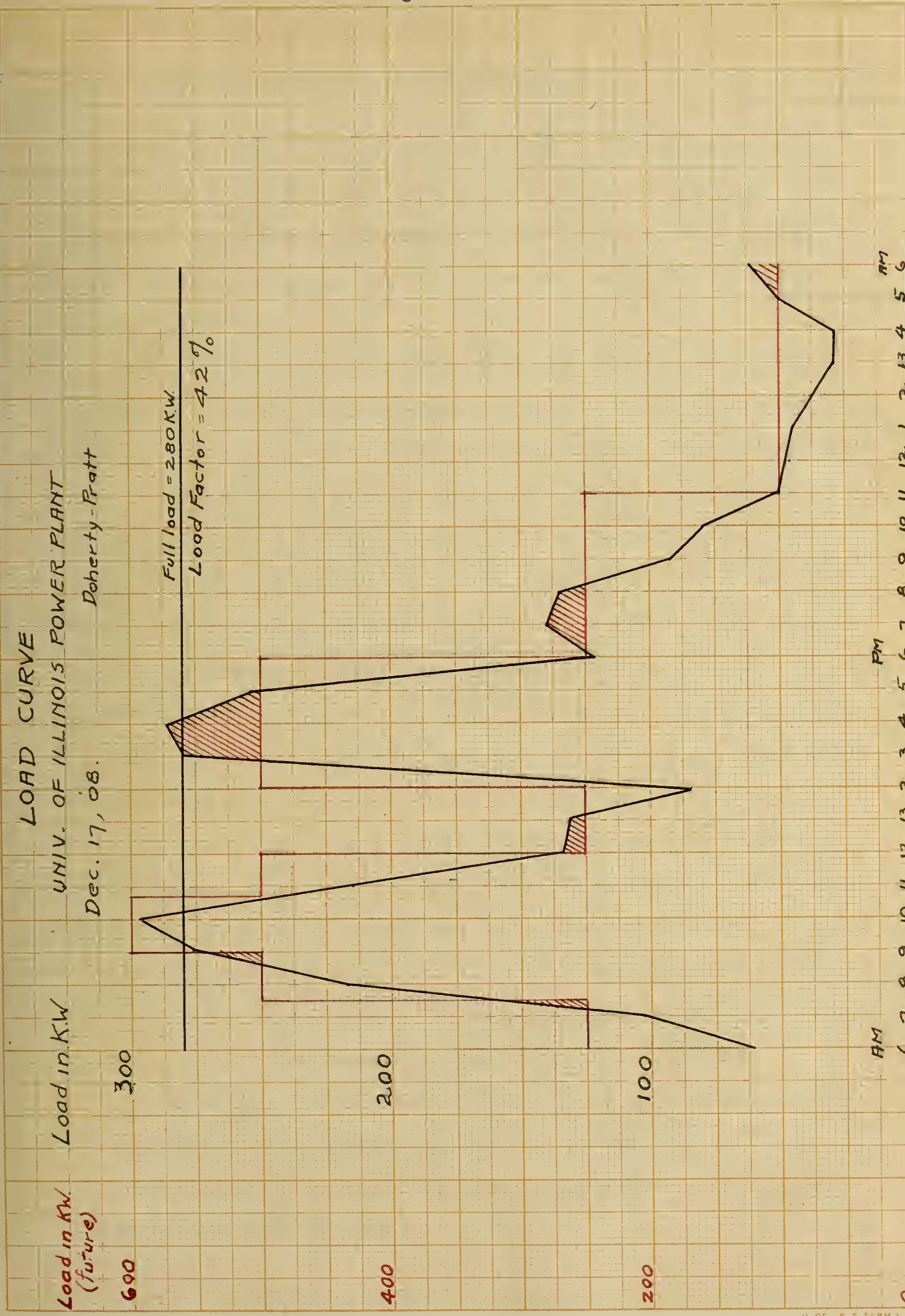
(f) Maximum load factor 42%

(g) Minimum load factor 11.5%


LOAD CURVE
UNIV. OF ILLINOIS POWER PLANT
March 17, '09.
Doherty - Pratt.
Full load = 280 K.W.
Load Factor 37%.
Load in K.W.
300
200
100
AM 6 7 8 9 10 11 12 1 2 3 4 5 PM 6 7 8 9 10 11 12 1 2 3 4 5 6 AM


LOAD CURVE
UNIV. OF ILLINOIS POWER PLANT
June 21, '08.
Doherty - Pratt.
Full load = 280 K.W
Load Factor 11.5%
Load in K.W.
300
200
100
AM
6 7 8 9 10 11 12 1 2 3 4 5 6
PM
7 8 9 10 11 12 1 2 3 4 5 6
AM


LOAD CURVE
UNIV. OF ILLINOIS POWER PLANT
Sept. 4, '08.
Doherty - Pratt.
Full load = 280 K.W.
Load Factor 18%
Load in K.W.
300
200
100
AM
6 7 8 9 10 11 12 1 2 3 4 5
PM
6 7 8 9 10 11 12 1 2 3 4 5 6
AM


LOAD CURVE
UNIV. OF ILLINOIS POWER PLANT
Dec. 17, 08.
Doherty - Pratt
Full load = 280 K.W.
Load Factor = 42%
Load in K.W.
Load in K.W. (future)
300
200
100
600
400
200
0
AM 6 7 8 9 10 11 12 1 2 3 4 5 PM 6 7 8 9 10 11 12 1 2 3 4 5 6 AM

DETERMINATION OF SIZE AND NUMBER OF UNITS.

It is probable that the future load will not alter the general shape of the load curve. Therefore, in order to determine the size and number of units, it will be assumed that the maximum peak of the load curve for December is six hundred kilowatts.

It is found that two machines of two hundred and fifty kilowatts capacity each, and one of one hundred kilowatts capacity will handle the load satisfactorily. This combination offers a flexible control of the load, and if all machines are in running condition, they can be handled so that those in operation will run at full load most of the time, and in no case will any of them be overloaded more than 10%, this overload occuring at the afternoon peak if the one hundred kilowatt machine is idle. If the one hundred kilowatt machine is out of service, the other two will be overloaded only 20% at the afternoon peak. If one of the two hundred and fifty kilowatt units is out of order, the other two alternators will be overloaded 50% for about one hour. Thus the most severe operating conditions can be met with this combination of units.

The red lines on the load curve for December show the way the combinations are made. The cross hatched areas represent the overload on the machines under normal conditions.

In computing the operating costs for a comparison of gas engines and steam turbines, a load factor of 30% will be assumed. This, it is believed, is a fair average of the daily load factors for one year.

A GENERAL CONSIDERATION OF STEAM TURBINES AND GAS ENGINES.

STEAM TURBINES.

Simplicity is probably the most striking feature of the steam turbine. Some of the features that make the turbine simple are:

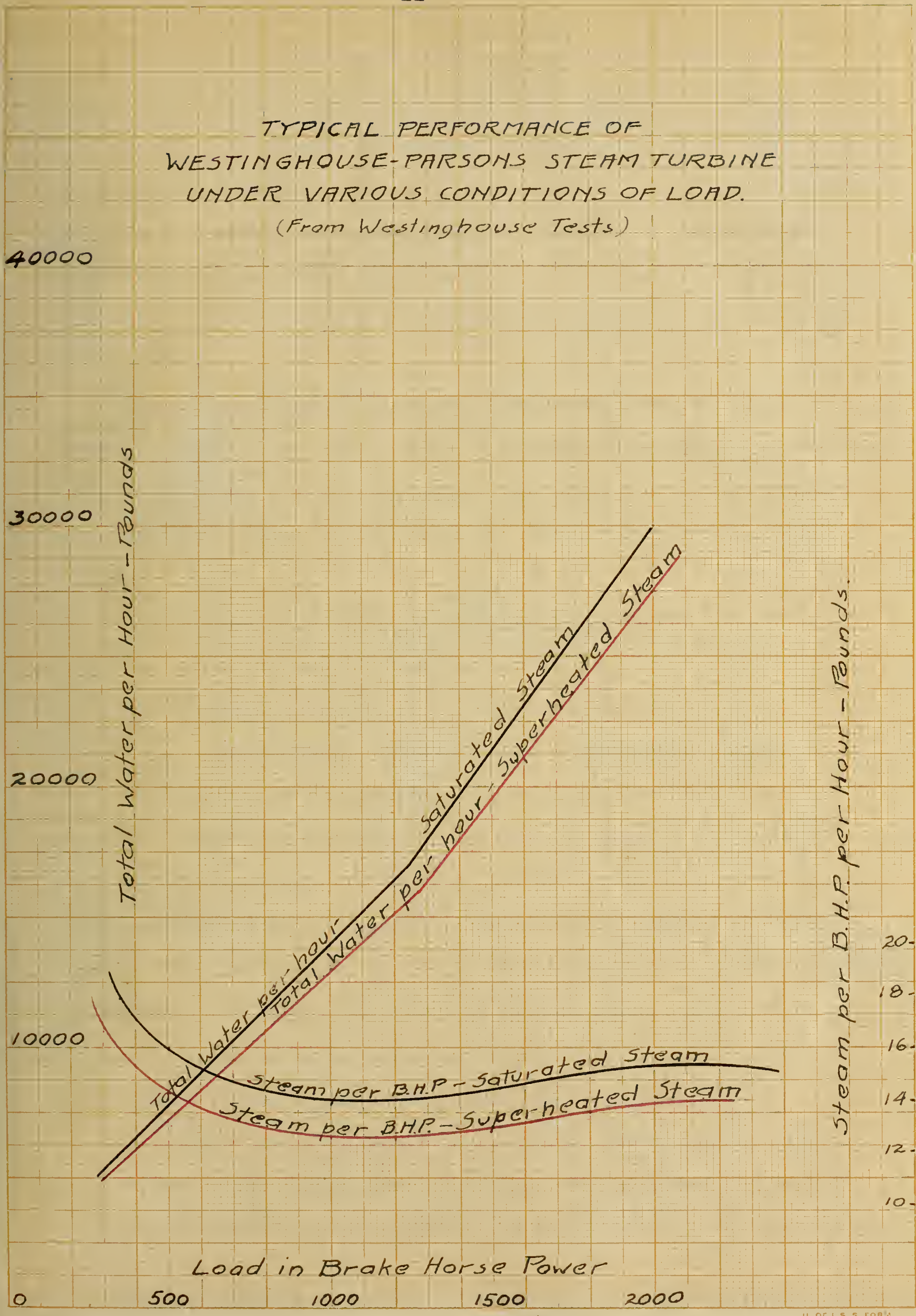
(1) There are no leaky pistons to cause trouble; no reciprocating parts to be keyed up.

(2) Packing, which, in reciprocating engines, often entails considerable trouble and cost of maintainance, is not used at all in turbines.

(3) The turbine uses no cylinder oil. Therefore, the condensed steam is free from oil.

The steam turbine weighs many times less than a gas engine or a Corliss engine of the same capacity. It occupies only 25% as much floor space as the vertical Corliss engine, and only 16% as much as the horizontal Corliss. A good illustration of how this feature of the steam turbine was taken advantage of, is the new installation made by the B.F. Goodrich Company of Akron, Ohio. With the original power plant and equipment, there was no possibility of extension, but by the installation of steam turbines, the generating capacity was doubled.

When a power plant is to be built in a city where floor space is very expensive, the compactness of the steam turbine must appeal to the designer.


TYPICAL PERFORMANCE OF
WESTINGHOUSE-PARSONS STEAM TURBINE
UNDER VARIOUS CONDITIONS OF LOAD.
(From Westinghouse Tests)
40000
30000
20000
10000
Total Water per Hour - Pounds
Steam per B.H.P. per Hour - Pounds
20
18
16
14
12
10
Total Water per hour - Saturated Steam
Total Water per hour - Superheated Steam
Steam per B.H.P - Saturated Steam
Steam per B.H.P. - Superheated Steam
Load in Brake Horse Power
0
500
1000
1500
2000

The actual performance of steam turbines under varying conditions usually met with in general power plant practice, is shown by the table and curves which will be found on accompanying pages.

These curves are based upon the results of tests of a Westinghouse Parsons Steam Turbine of standard construction, and the performance may be considered typical of machines of this type.

The diagonal lines show the steam condensed per hour at various loads. The curves show the steam consumption per horse power per hour at various loads. The upper curve corresponds to the upper "Water Line", and the lower curve to the lower "Water Line".

It will be noted from the curves that marked economy results from the use of superheated steam.

The operative conditions covered by the tests are;

(a) Condensing, saturated and superheated steam.

(b) One quarter rated load to 100% overload.

The Westinghouse Parsons Turbine is equipped with an automatic secondary valve, the duty of which is to open at some predetermined load and allow an extra supply of steam to enter the turbine in order that overloads may be handled without affecting the high efficiency at normal loads. The result of the operation of this valve is shown plainly by the bend in the "Water Lines" just after full load is passed. It is evident that the efficiency is slightly lowered after the secondary valve comes into operation, but a plant can better afford to operate at a slightly lower efficiency for the short

time of peak loads, than to install additional units to handle the peaks.

The difficulties experienced with lubrication and the destruction of valves and glands under the high temperatures have limited the use of superheated steam with the piston type of engine.

The turbine, however, has steam proof, frictionless glands and requires no internal lubrication. Its construction admits of the use of the highest superheat, and the steam may be expanded down to the lowest condenser pressure without great increase in bulk and friction which renders the use of high vacua ineffective in reciprocating engines. Higher economies are thus possible in turbine work.

Experience has shown that reciprocating engines grow less economical as they age and wear, also that the steam turbine retains its original economy through years of service. The bearings are the only rubbing parts, but, being flooded with oil, the shaft never comes in metallic contact with the bearing. The blades retain their original shape, and the low steam velocities employed in this type of turbine, prevent the erosive action which accompanies the use of high velocity steam as in the case of the De Laval type.

For parallel operation of alternators, a uniform driving torque is very essential. The speed of the steam turbine is uniform at all parts of its revolution, which is not true in the case of the reciprocating engine. This renders the turbine especially adapted for service where two alternators are to

be run in parallel.

The turbine has no reciprocating thrusts or vibrations to be absorbed, as does the reciprocating engine. The turbine does not even have to be bolted to its support. Any foundation strong enough to maintain alignment and to bear the weight of the turbine is sufficient. Therefore, there is a great saving in the construction of a foundation, not only on this ground, but also because the foundation will be smaller on account of the turbine being of smaller proportions than a reciprocating engine of the same capacity.

Turbines are usually shipped with all the main parts assembled and permanently adjusted. Where weeks and months are required to erect a piston engine, the turbine requires but comparatively few days. Cases are not uncommon where turbines of six hundred kilowatts capacity have been supplying commercial current within less than a week from the time of delivery.

The fact that one company alone has installed turbines aggregating a capacity of sixty four thousand kilowatts, in such plants as the Western Pennsylvania Railway and Lighting Company of Connelsville, Pennsylvania, Yale and Towne Manufacturing Company, and the Johnston Harvesting Company, is convincing that the application of the steam turbine to general power work is permanently established.

RESULTS OF TESTS.

The following tables and curves show the results of both shop tests and tests of plants in actual operation.

FRANCIS HODGKINSON.

	28 Inches.
	150

TESTS OF WESTINGHOUSE-PARSONS STEAM TURBINES.

SIZE OF TURBINE	400 K. W.										
VACUUM IN EXHAUST	26 Inches.										27 Inches.
THROTTLE PRESSURE LBS. GAUGE	125			140				160			150
CONDITION OF THE STEAM	Dry and Satur'd.			Quality=99%				Dry and Saturat'd			Dry and Saturated.
REVOLUTIONS PER MINUTE	3,600			3,600				3,600			3,600
TURBINE NUMBER	28			35				51			47
1 Steam pressure lbs. per gauge	125.6	124.9	130.6	142.8	144.0	144.5	138.2	151.6	151.4	149.8	153.4
2 Vacuum referred to 30-inch barom'r	26.0	26.02	26.03	26.0	26.0	26.0	26.0	26.06	26.06	26.06	27.04
3 Superheat, degrees Fahrenheit	2.5	....	....	....	....	....	....	....	2.0	4 0	....
4 Quality of the steam	....	.999	.999	.989	.989	.99	.948	1.00	....	....	1.00
5 Revolutions per minute	3,536	3,655	3,545	3,511	3,557	3,582	3,589	3,641	3,699	3,593	3,628
6 Load in kilo-watts	....	....	....	....	....	....	....	....	....	....	438.1
7 Load in electrical horse-power	....	....	....	....	....	....	....	....	....	....	687.8
8 Load in brake horse-power	580.1	467.2	326.0	623.4	508.2	381.0	10.7	610.8	451.4	266.1	....
9 Total pounds of steam per hour	8,940	7,481	5,834	9,502	7,992	6,311	1,035	8,917	6,916	4,542	8,739
10 Pounds of steam per E. H. P. hour	....	....	....	....	....	....	....	....	....	....	14.89
11 Pounds of steam per B. H. P. hour	15.41	16.36	17.89	15.24	15.73	16.66	....	14.69	15.32	17.06	....
12 Load in per cent. of full load	98	77	55	105	86	64	2	103	77	45	109
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**

SIZE OF TURBINE	400 K. W.										
VACUUM IN EXHAUST	27 Inches.										
THROTTLE PRESSURE LBS. GAUGE	150										
CONDITION OF THE STEAM	Dry and Saturated.							5° Superheat			
REVOLUTIONS PER MINUTE	3,600							3,600			
TURBINE NUMBER	47		49			55		53			
1 Steam pressure lbs. per gauge	153.2	153.1	152	166	155	*152	*155	140.9	148.3	154	153.5
2 Vacuum referred to 30-inch barom'r	27.11	27.06	27.15	27.2	27.25	27.01	27.01	27.0	27.0	27	27.0
3 Superheat, degrees Fahrenheit	....	....	3.0	5.0	....	....	....	7.0	5.0	4	2.0
4 Quality of the steam	1.00	.998	....	....	.997	1.00	1.00	....	....	....	....
5 Revolutions per minute	3,676	3,683	3,620	3,565	3,577	3,497	3,649	3,541	3,563	3,664	3,683
6 Load in kilo-watts	298.4	211.6	....	....	....	....	....	....	....	....	....
7 Load in electrical horse-power	400.0	283.6	....	....	....	....	....	....	....	....	....
8 Load in brake horse-power	....	....	651	435	261	691	593.6	607.7	441.2	288.9	152.6
9 Total pounds of steam per hour	6,205	4,774	9,200	6,472	4,411	9,734	8,514	8,882	6,625	4,774	2,881
10 Pounds of steam per E. H. P. hour	15.61	16.81	....	....	....	....	....	....	....	....	....
11 Pounds of steam per B. H. P. hour	....	....	14.15	14.88	16.9	14.1	14.35	14.61	15.01	16.52	18.88
12 Load in per cent. of full load	75	53	110	74	44	119	100	103	75	49	26
	12	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**

SIZE OF TURBINE	400 K. W.										
VACUUM IN EXHAUST	27 Inches.							28 Inches.			
THROTTLE PRESSURE LBS. GAUGE	150							150			
CONDITION OF THE STEAM	5° Superheat	100° Superheat.						Dry Saturated.			
REVOLUTIONS PER MINUTE	3,600	3,600						3,600			
TURBINE NUMBER	53	37			39			55			
1 Steam pressure lbs. per gauge	154	149.8	160.6	152.8	155.2	147.6	155	*153.6	*154.6	*156	*155.8
2 Vacuum referred to 30-inch barom'r	27	27.01	27.0	27.0	27.05	27.0	27	28.01	27.98	27.92	28.01
3 Superheat, degrees Fahrenheit	....	100	103.5	95.6	97.6	104.2	103.1	....	....	....	....
4 Quality of the steam	.998	....	....	....	....	....	....	1.00	.999	1.00	.996
5 Revolutions per minute	3,602	3,492	3,570	3,606	3,482	3,509	3,530	3,480	3,545	3,583	3,602
6 Load in kilo-watts	....	....	....	....	411.2	311.7	219	....	....	....	....
7 Load in electrical horse-power	....	....	....	....	551.1	417.9	293.7	....	....	....	....
8 Load in brake horse-power	9.2	650.3	481	254.4	....	....	....	729	593.2	448	241
9 Total pounds of steam per hour	953.6	8,778	6,657	4,039.5	7,425	5,780	4,272	9,928	8,269	6,488	3,876
10 Pounds of steam per E. H. P. hour	....	....	....	....	13.47	13.83	14.64	....	....	....	....
11 Pounds of steam per B. H. P. hour	....	13.5	13.84	15.87	....	....	....	13.62	13.91	14.48	16.05
12 Load in per cent. of full load	....	110	82	43	103	78	55	123	100	76	41
	23	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**

SIZE OF TURBINE	400 K. W.									
VACUUM IN EXHAUST	28 Inches.									
THROTTLE PRESSURE LBS. GAUGE	150									
CONDITION OF THE STEAM	Dry Saturated.				45° Superheat.					
REVOLUTIONS PER MINUTE	3,600				3,600					
TURBINE NUMBER	55	36			62					
1 Steam pressure lbs. per gauge	*152	151.7	154.5	153	143.5	149.6	150.3	152.1	150.7	150
2 Vacuum referred to 30-inch barom'r	28.01	28.0	28.0	28	27.78	28.03	28.0	28.01	28.02	28.02
3 Superheat, degrees Fahrenheit	....	....	....	....	45.0	44.0	42.0	45.0	41.0	45.0
4 Quality of the steam	.986	.992	.992	1.00	....	....	....	....	....	....
5 Revolutions per minute	3,662	3,528	3,670	3,591	3,414	3,436	3,478	3,611	3,526	3,549
6 Load in kilo-watts	....	402	292.2	198.7	....	....	....	....	....	....
7 Load in electrical horse-power	....	639	391.7	266.3	....	....	....	....	....	....
8 Load in brake horse-power	6.3	....	....	....	1,028.2	824.6	755.9	621.5	424.6	258.1
9 Total pounds of steam per hour	706	8,169	6,172	4,640	14,637	11,020	9,998	8,417	6,015	4,015
10 Pounds of steam per E. H. P. hour	....	15.15	15.75	17.42	....	....	....	....	....	....
11 Pounds of steam per B. H. P. hour	....	....	....	....	14.13	13.36	13.23	13.56	14.16	15.55
12 Load in per cent. of full load	1	100	73	60	174	140	129	105	72	44
	34	**35**	**36**	**37**	**38**	**39**	**40**	**41**	**42**	**43**

SIZE OF TURBINE	400 K. W.										
VACUUM IN EXHAUST	28 Inches.										
THROTTLE PRESSURE LBS. GAUGE	150										
CONDITION OF THE STEAM	100° Superheat.				150° Superheat.			180° Supe't		190° Superheat.	
REVOLUTIONS PER MINUTE	3,600				3,600			3,600		3,600	
TURBINE NUMBER	55				54			55		67	
1 Steam pressure lbs. per gauge	*150	*150.3	*154.5	*153.3	150.6	149.4	150.2	*160.2	*153.6	148.4	147.9
2 Vacuum referred to 30-inch barom'r	28.01	28.01	28.01	28.01	28.0	28.0	28.0	28.08	28.1	28.0	28.0
3 Superheat, degrees Fahrenheit	104	104	106	88	139	158.8	150	182	180	192	185
4 Quality of the steam	....	....	....	....	....	....	....	....	....	....	....
5 Revolutions per minute	3,458	3,544	3,581	3,627	3,538	3,586	3,595	3,478	3,543	3,651	3,571
6 Load in kilo-watts	....	....	....	....	....	....	....	....	....	428.4	303.8
7 Load in electrical horse-power	....	....	....	....	....	....	....	....	....	571.5	407.2
8 Load in brake horse-power	759	693	445	264	626	451	296.8	763	592	....	....
9 Total pounds of steam per hour	9,157	7,408	5,728	3,504	7,426	5,324	3,919	8,520	6,795	7,444	5,626
10 Pounds of steam per E. H. P. hour	....	....	....	....	....	....	....	....	....	13.02	13.81
11 Pounds of steam per B. H. P. hour	12.06	12.5	12.87	14.48	11.86	11.87	13.2	11.17	11.46	....	....
12 Load in per cent. of full load	128	100	75	45	106	76	50	129	100	106	76
	44	**45**	**46**	**47**	**48**	**49**	**50**	**51**	**52**	**53**	**54**

SIZE OF TURBINE	400 K. W.	1,000 K. W.				1,250 K. W.					
VACUUM IN EXHAUST	28 Inches.	27 Inches.				25 Inches.			26 Inches.		
THROTTLE PRESSURE LBS. GAUGE	150	130				150			150		
CONDITION OF THE STEAM	190° Superheat.	Quality=100%.				Quality=98%.			Quality=98%.		
REVOLUTIONS PER MINUTE	3,600	1,500				1,500			1,500		
TURBINE NUMBER	67	15				17			17		
1 Steam pressure lbs. per gauge	149.1	132.6	132.7	134.3	139	148.7	150.6	151	150.5	150	151
2 Vacuum referred to 30-inch barom'r	28.0	27.02	27.0	27.08	26.83	25.07	25.08	25.18	26.05	25.92	26.22
3 Superheat, degrees Fahrenheit	157	....	....	....	....	....	....	....	....	....	....
4 Quality of the steam	....	.999	.999	.999	.998	.98	.98	.98	.98	.98	.98
5 Revolutions per minute	3,583	1,489	1,498	1,508	1,513	1,498	1,503	1,600	1,503	1,503	1,500
6 Load in kilo-watts	197.8	1,101.7	786.7	530.7	380.1	1,506	914	310	1,519	897	306
7 Load in electrical horse-power	265.1	1,476.8	1054.5	711.4	509.4	2,015	1,224	417	2,038	1,201	410
8 Load in brake horse-power	....	....	....	....	....	....	....	....	....	....	....
9 Total pounds of steam per hour	4,126	21,984	16,867	12,775	10,547	32,924	23,030	11,713	32,039	21,985	10,891
10 Pounds of steam per E. H. P. hour	15.56	14.9	15.99	17.95	20.75	16.32	18.82	28.1	15.72	18.29	26.62
11 Pounds of steam per B. H. P. hour	....	....	....	....	....	....	....	....	....	....	....
12 Load in per cent. of full load	50	110	79	53	38	120	73	25	121	72	24
	55	**56**	**57**	**58**	**59**	**60**	**61**	**62**	**63**	**64**	**65**

SIZE OF TURBINE	1,250 K. W.										
VACUUM IN EXHAUST	27 Inches.										
THROTTLE PRESSURE LBS. GAUGE	160										
CONDITION OF THE STEAM	Quality=98%.			Quality=99%.				50° Superheat.			
REVOLUTIONS PER MINUTE	1,500			1,200				1,500			
TURBINE NUMBER	17			32				17			
1 Steam pressure lbs. per gauge	147	150.4	148	147.7	146.5	148.6	149.2	149.8	149.6	149.5	151
2 Vacuum referred to 30-inch barom'r	26.93	26.99	26.87	27.05	27.06	27.07	27.08	27.01	26.92	27.06	26.68
3 Superheat, degrees Fahrenheit	....	....	....	....	....	....	....	50.0	51.0	49.0	54.0
4 Quality of the steam	.98	.98	.98	.992	.994	.992	.991	....	....	....	....
5 Revolutions per minute	1,495	1,502	1,500	1,186	1,203	1,206	1,221	1,602	1,503	1,500	1,500
6 Load in kilo-watts	1,529	963	254	1,530.2	1,154.6	792.1	392.5	1,475	1,253	877	302
7 Load in electrical horse-power	2,050	1,285	340	2,051.2	1.547.8	1,061.6	526.1	1,978	1,681	1,173	405
8 Load in brake horse-power	....	....	....	....	....	....	....	....	....	....	....
9 Total pounds of steam per hour	31,192	21,918	9,109	30,358	23,233	18,273	10,625	27,246	24,544	19,223	9,773
10 Pounds of steam per E. H. P. hour	15.22	17.06	26.79	14.8	15.01	17.21	20.19	13.82	14.6	16.35	24.2
11 Pounds of steam per B. H. P. hour	....	....	....	....	....	....	....	....	....	....	....
12 Load in per cent. of full load	122	77	20	123	92	63	31	118	100	70	24
	66	**67**	**68**	**69**	**70**	**71**	**72**	**73**	**74**	**75**	**76**

SIZE OF TURBINE	1,250 K. W.								
VACUUM IN EXHAUST	27.5 Inches.						28 Inches.		
THROTTLE PRESSURE LBS. GAUGE	150						150		
CONDITION OF THE STEAM	Dry Steam.		25° Superheat.				Quality=98%.		
REVOLUTIONS PER MINUTE	1,500		1,500				1,500		
TURBINE NUMBER	31		31				17		
1 Steam pressure lbs. per gauge	†149.4	†146.2	146	144.3	147.6	155.1	148.8	150	151.8
2 Vacuum referred to 30-inch barom'r	27.5	27.85	27.48	27.62	27.46	27.55	27.42	28.12	28.98
3 Superheat, degrees Fahrenheit	....	....	28	28	28	30	....	....	....
4 Quality of the steam	.994	.995	....	....	....	....	.988	.975	.979
5 Revolutions per minute	1,456	1,477	1,476	1,491	1,503	1,507	1,499	1,502	1,500
6 Load in kilo-watts	1,510.4	1,019.1	1,557.6	1,239.8	767.9	383.4	1,545	935	262
7 Load in electrical horse-power	2,024.6	1,365	2,087.8	1,662	1,028.1	513.9	2,065	1,252	249.2
8 Load in brake horse-power	....	....	....	....	....	....	....	....	....
9 Total pounds of steam per hour	28,333	20,915	28,537	23,181	16,507	10,302	3,456	19,703	7,392
10 Pounds of steam per E. H. P. hour	13.99	15.31	13.67	13.94	16.05	20.04	14.73	15.75	21.8
11 Pounds of steam per B. H. P. hour	....	....	....	....	....	....	....	....	....
12 Load in per cent. of full load	120	81	125	99	61	31	124	75	21
	77	**78**	**79**	**80**	**81**	**82**	**83**	**84**	**85**

SIZE OF TURBINE	1,250 K. W.			1,250 K. W.							
VACUUM IN EXHAUST	28 Inches.			25 Inches.		26 Inches.		27 Inches.			
THROTTLE PRESSURE LBS. GAUGE	150			150		150		150			
CONDITION OF STEAM	140° Superheat.			Dry Satur'd.		Dry Satur'd.		Dry Saturated.			
REVOLUTIONS PER MINUTE	1,500			1,200		1,200		1,200			
TURBINE NUMBER	17			43		43		41			
1 Steam pressure lbs. per gauge	154	149.5	148.9	146.4	148.4	147	143.9	‡141.8	‡144.6	‡148	‡147.1
2 Vacuum referred to 30-inch barom'r	28.1	28.04	28.17	25.01	25.05	26.01	26.05	26.79	26.05	27.05	27.11
3 Superheat, degrees Fahrenheit	141	139	138	2	3	1	....	....	....	....	....
4 Quality of the steam	....	....	....	....	....	....	1.00	1.00	1.00	1.00	1.00
5 Revolutions per minute	1,500	1,500	1,503	1,199	1,201	1,198	1,202	1,197.4	1,200	1,201	1,196
6 Load in kilo-watts	1,512	904	306	....	....	....	....	1,988.9	1,713.5	1,489.4	1,321.6
7 Load in electrical horse-power	2,030	1,210	412	....	....	....	....	2,666	2,297.1	1,996.5	1,771.4
8 Load in brake horse-power	....	....	....	2,008.3	1,004.4	2,002.3	1,007	....	....	....	....
9 Total pounds of steam per hour	25,685	17,042	8,108	28,902	16,809	28,236	16,106	40,547	33,036	28,208	25,712
10 Pounds of steam per E. H. P. hour	12.66	14.1	19.68	....	....	....	....	15.21	14.38	14.13	14.52
11 Pounds of steam per B. H. P. hour	....	....	....	14.39	16.73	14.10	15.99	....	....	....	....
12 Load in per cent of full load	121	72	24	110	55	110	55	169	137	119	106
	86	**87**	**88**	**89**	**90**	**91**	**92**	**93**	**94**	**95**	**96**

SIZE OF TURBINE	1,250 K. W.										
VACUUM IN EXHAUST	27 Inches.										
THROTTLE PRESSURE LBS. GAUGE	150										
CONDITION OF STEAM	Dry Saturated.							75° Superheat.			
REVOLUTIONS PER MINUTE	1,200				1,200			1,200			
TURBINE NUMBER	41				43			41			
1 Steam pressure lbs. per gauge	‡146.5	‡146.8	‡151.4	‡160.3	146.3	145.9	148.7	‡146.3	‡147.7	‡151	‡151.9
2 Vacuum referred to 30-inch barom'r	27.11	27.11	27.1	27.08	27	27	26.95	27.1	27.1	27.15	27.07
3 Superheat, degrees Fahrenheit	....	....	....	....	2	2	2	76	76	77	77
4 Quality of the steam	1.00	1.00	1.00	.999	....	....	....	....	....	....	....
5 Revolutions per minute	1,197	1,199	1,201	1,201	1,199	1,199	1,202	1,201	1,205	1,209	1,213
6 Load in kilo-watts	989.6	656	342.7	197	....	....	....	1,293.9	986.2	664.7	333.6
7 Load in electrical horse-power	1,326.5	879.3	459.4	264	....	....	....	1,734.4	1,322	891	447.1
8 Load in brake horse-power	....	....	....	....	2,005.3	1,499.7	1,004	....	....	....	....
9 Total pounds of steam per hour	20,254	15,074	9,732	7,150	27,248	21,189	15,241	23,903	19,108	14,181	9,170
10 Pounds of steam per E. H. P. hour	15.27	17.14	21.18	27.68	....	....	....	13.78	14.45	15.9	20.51
11 Pounds of steam per B. H. P. hour	....	....	....	....	13.59	14.13	15.18	....	....	....	....
12 Load in per cent of full load	79	53	28	16	110	82	55	104	79	53	27
	97	**98**	**99**	**100**	**101**	**102**	**103**	**104**	**105**	**106**	**107**

SIZE OF TURBINE	1,250 K. W.										
VACUUM IN EXHAUST	27 Inches.	28 Inches.									
THROTTLE PRESSURE LBS. GAUGE	150	160									
CONDITION OF STEAM	75° Superheat.	Dry Saturated.					75° Superheat.				100° Superheat.
REVOLUTIONS PER MINUTE	1,200	1,200					1,200				1,200
TURBINE NUMBER	41	41			43		41				43
1 Steam pressure lbs. per gauge	‡151.8	‡146.1	‡146.8	‡151	146.9	149	‡146	‡147.6	‡150.8	‡151.8	147
2 Vacuum referred to 30-inch barom'r	27.15	28.08	28.1	28.05	28.1	28	28.1	28.1	28.05	28.05	27.95
3 Superheat, degrees Fahrenheit	77	....	....	....	2	2	78	77	77	76	102.3
4 Quality of the steam	....	1.00	1.00	1.00	....	....	....	....	....	....	....
5 Revolutions per minute	1,201	1,197	1,201	1,198	1,200	1,204	1,199	1,204	1,214	1,217	1,203
6 Load in kilo-watts	191	1,364	972	334.8	....	....	1,274.2	977.6	333.2	198.4	....
7 Load in electrical horse-power	256	1,828.3	1,303	448.7	....	....	1,708	1,310.5	446.6	266.1	....
8 Load in brake horse-power	....	....	....	....	1,578.2	911.5	....	....	....	....	1,808
9 Total pounds of steam per hour	6,734	25,639	19,334	9,295	21,286	13,337	22,504	18,180	8,420	6,300	23,180
10 Pounds of steam per E. H. P. hour	26.3	14.02	14.91	20.71	....	....	13.17	13.87	18.86	28.68	....
11 Pounds of steam per B. H. P. hour	....	....	....	....	13.49	14.63	....	....	....	....	12.82
12 Load in per cent of full load	15	109	78	27	87	50	102	78	27	16	99
	108	**109**	**110**	**111**	**112**	**113**	**114**	**115**	**116**	**117**	**118**

SIZE OF TURBINE	1,250 K. W.			2,600 K. W. §		
VACUUM IN EXHAUST	28 Inches.			27.5 Inches.		
THROTTLE PRESSURE LBS. GAUGE	160			190		
CONDITION OF STEAM	100° Superheat.			190° Superheat		
REVOLUTIONS PER MINUTE	1,200			1,360		
TURBINE NUMBER	43					
1 Steam pressure lbs. per gauge	146.4	147.2	148.8	188	188	186
2 Vacuum referred to 30-inch barom'r	28.02	27.97	28.02	27	27.5	27.98
3 Superheat, degrees Fahrenheit	104	102.3	102	214	180	186
4 Quality of the steam	....	....	....	....	....	....
5 Revolutions per minute	1,202	1,203	1,199	1,360	1,360	1,360
6 Load in kilo-watts	....	....	....	2,995	2,518	1,945
7 Load in electrical horse-power	....	....	....	4,010	3,378	2,608
8 Load in brake horse-power	1,655.8	1,298.4	815.4	....	....	....
9 Total pounds of steam per hour	21,302	17,009	11,671	44,236	39,356	30,867
10 Pounds of steam per E. H. P. hour	....	....	....	11.02	11.57	11.83
11 Pounds of steam per B. H. P. hour	12.86	13.09	13.70	....	....	....
12 Load in per cent of full load	90	71	34	115	97	75
	119	**120**	**121**	**122**	**123**	**124**

* Test made by Mr. F. W. Dean, of Dean & Main, Boston.

† Tests made by a board of naval engineers.

‡ Tests witnessed and verified by engineers of the staff of Julian Kennedy, Pittsburg, Pa.

§ Built by the Brown-Boveri Company.

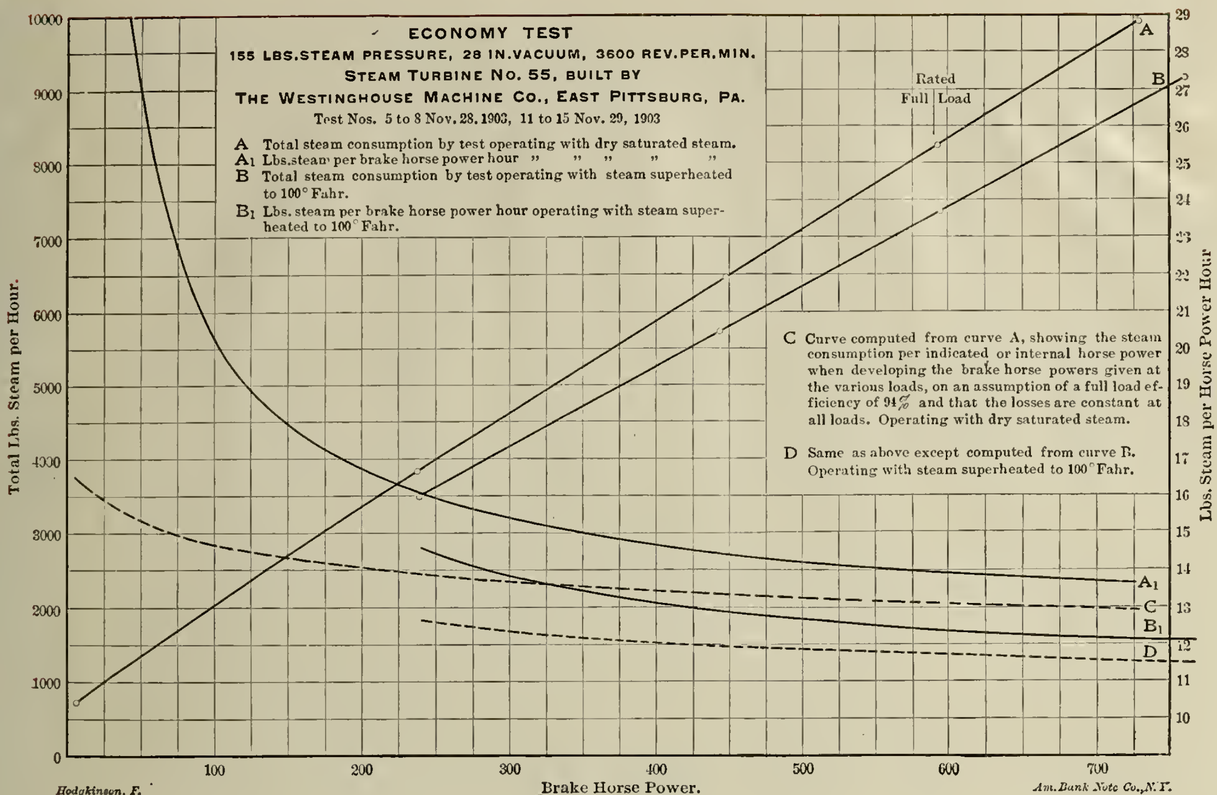
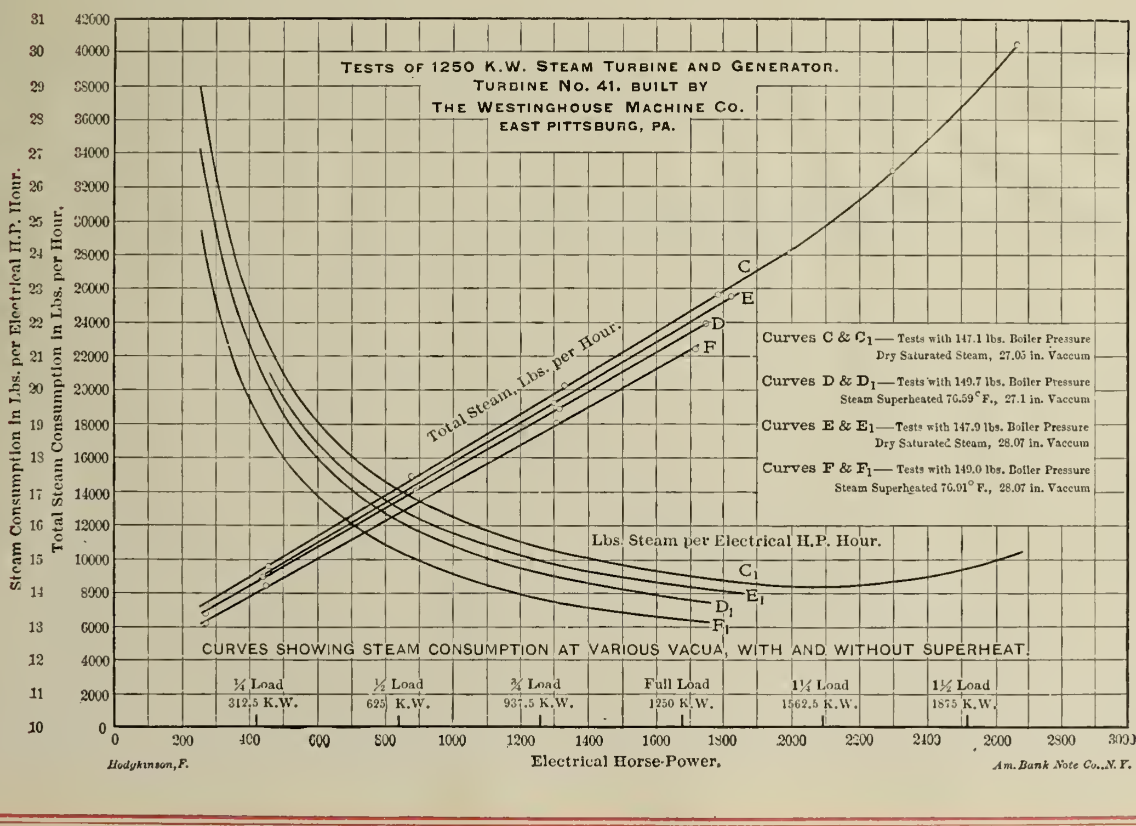

ECONOMY TEST
155 LBS. STEAM PRESSURE, 28 IN. VACUUM, 3600 REV. PER. MIN.
STEAM TURBINE NO. 55, BUILT BY
THE WESTINGHOUSE MACHINE CO., EAST PITTSBURG, PA.
Test Nos. 5 to 8 Nov. 28, 1903, 11 to 15 Nov. 29, 1903
A Total steam consumption by test operating with dry saturated steam.
A1 Lbs. steam per brake horse power hour " " " "
B Total steam consumption by test operating with steam superheated to 100° Fahr.
B1 Lbs. steam per brake horse power hour operating with steam superheated to 100° Fahr.
C Curve computed from curve A, showing the steam consumption per indicated or internal horse power when developing the brake horse powers given at the various loads, on an assumption of a full load efficiency of 94% and that the losses are constant at all loads. Operating with dry saturated steam.
D Same as above except computed from curve B. Operating with steam superheated to 100° Fahr.
Rated Full Load
Total Lbs. Steam per Hour.
Lbs. Steam per Horse Power Hour
Brake Horse Power.
Hodgkinson, F.
Am. Bank Note Co., N.Y.

FIG. 373.


TESTS OF 1250 K.W. STEAM TURBINE AND GENERATOR.
TURBINE NO. 41. BUILT BY
THE WESTINGHOUSE MACHINE CO.
EAST PITTSBURG, PA.
Curves C & C1 — Tests with 147.1 lbs. Boiler Pressure Dry Saturated Steam, 27.05 in. Vaccum
Curves D & D1 — Tests with 149.7 lbs. Boiler Pressure Steam Superheated 76.59° F., 27.1 in. Vaccum
Curves E & E1 — Tests with 147.9 lbs. Boiler Pressure Dry Saturated Steam, 28.07 in. Vaccum
Curves F & F1 — Tests with 149.0 lbs. Boiler Pressure Steam Superheated 76.01° F., 28.07 in. Vaccum
Total Steam, Lbs. per Hour.
Lbs. Steam per Electrical H.P. Hour.
CURVES SHOWING STEAM CONSUMPTION AT VARIOUS VACUA, WITH AND WITHOUT SUPERHEAT.
¼ Load 312.5 K.W.
½ Load 625 K.W.
¾ Load 937.5 K.W.
Full Load 1250 K.W.
1¼ Load 1562.5 K.W.
1½ Load 1875 K.W.
Steam Consumption in Lbs. per Electrical H.P. Hour.
Total Steam Consumption in Lbs. per Hour.
Electrical Horse-Power.
Hodgkinson, F.
Am. Bank Note Co., N.Y.

GAS ENGINES.

The past decade has seen a great development in gas engines and their successful application to power station work. The operation of stations in which gas engines have been installed, has led to the following conclusions about this type of engine:

(1) Ability to handle variable loads.

(2) Regulation suitable for alternating current parallel operation.

(3) Effect of misfires negligible.

(4) Sufficient reliability for regular daily service.

(5) Deterioration from wear quite normal.

(6) Oil and water consumption low.

(7) Automatic starting system quite sufficient for any emergency.

The predominating features of the gas engine are:

(1) Self-contained construction giving automatic lubrication, protection of parts, and a low cost of attendance and maintenance.

(2) Single acting principle, permitting of high speeds with smooth running. The engine is thus particularly suited to drive direct connected electric generators, in which exacting service it has proven distinctly successful.

EFFICIENCY.

A noted engineer has said that an installation consisting of Gas Producers and four cycle, four cylinder gas engines,

properly installed and operated, is the most economical source of power in existence today.

The thermal efficiency of the gas engine is very high compared with that of other heat engines, because it operates between greater temperature limits, and at the same time has the mechanical perfection of other engines.

SPEED.

The speed regulation of the gas engine has always been, until the last few years, one of the greatest barriers between this type of engine and its application to electrical work. It has not been so much the speed variation per minute that has troubled the designer, but the variations during each revolution.

It is an inherent characteristic of the reciprocating engine to have different speeds at the different events of the stroke, and, in case of the gas engine, this trouble is magnified on account of the heavy power impulses at the instants of explosion. These difficulties have been overcome in the following ways:

(1) Regulation of revolutions per minute

(a) Governor, which controls the supply of fuel

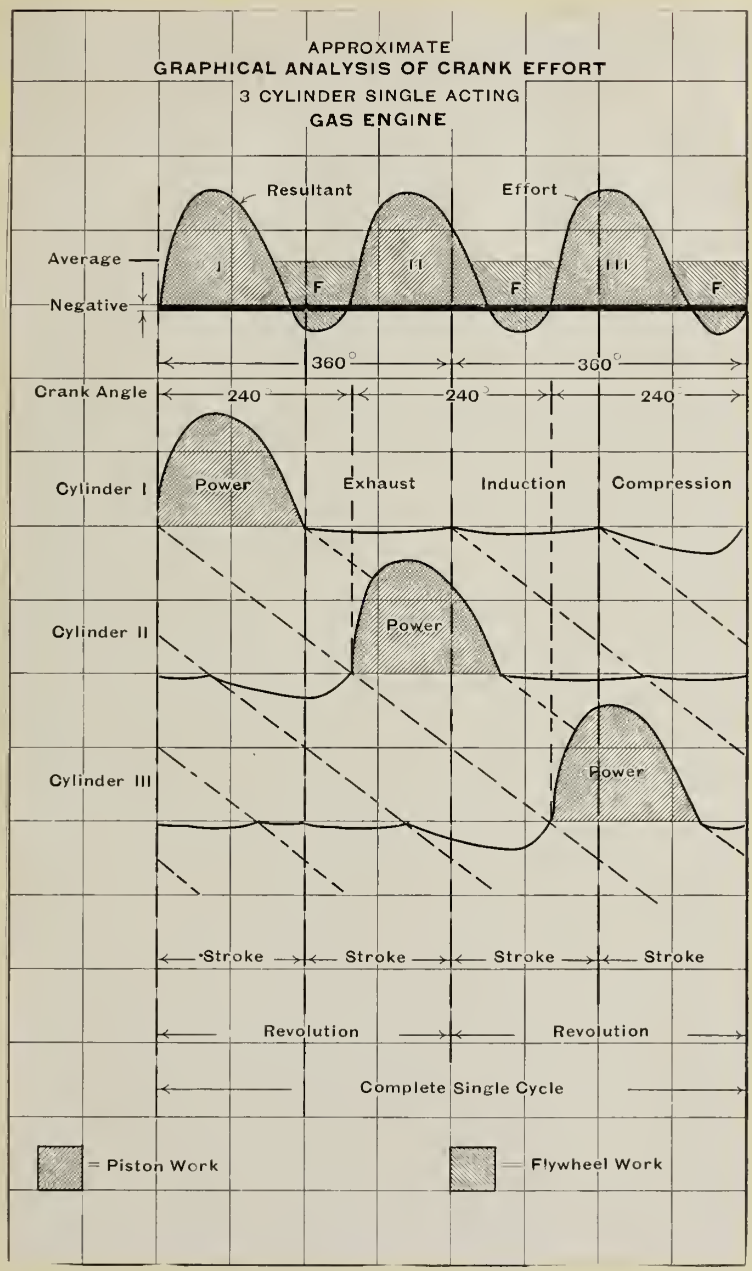
(2) Variation of speed per revolution

(a) Fly wheel

(b) A number of cylinders

The fly wheel stores up energy at points of the stroke where there is an excess of energy developed, and delivers it at points where energy is lacking. However, this is not sufficient in case of the single cylinder gas engine unless the fly wheel be of

abnormal size. If the engine has more than one cylinder,say three,the cranks are spaced at 120 degrees,and the power impulses occur regularly at every 240 degrees of the revolution,which has been found sufficient for the most exacting power work.



The above diagram will show the crank effort of the engine as modified by the fly wheel inertia. It is evident that for a uniform crank effort, which is very desirable where alternators are to be run in synchronism, the greater number of cylinders, and therefore power impulses per stroke, the nearer this condition will be approached, but of course the number of cylinders is limited by mechanical difficulties.

The application of the gas engine to electrical work has been the outcome of a perfected speed control, as well as of high efficiency obtained with this type of engine. If in the parallel operation of alternators, one prime mover tends to run faster than the others, there will result high surges of current. Even with perfect speed under normal conditions, misfires in the engine are apt to cause a fluctuation in speed which may result in a surge. However, Mr. J. R. Bibbins of the Westinghouse Company says, "The effect of misfires on parallel operation has been the subject of much conjecture, and it is of interest to know that, although misfires occur now and then as they are bound to do, in not a single instance have electrical troubles resulted during normal operation. While one cylinder is entirely isolated by a defective igniter, it is, of course, probable that some surging would result, but misfires that do occur are so seldom continued and are so easily remedied that no trouble whatever is apprehended from this source."

The following table shows the results of a speed test on a three hundred and fifty kilowatt machine, which was subjected to the severest sort of a test. It shows that on an instantaneous

load test,the drop in speed was only 4.6%,and under normal operation it is not probable that such a jump in the load would occur.

TABLE NO. 7 SPEED VARIATION TESTS

Speed, r.p.m.	155	154.0	152.0	150.0	149.0	148.0
Volts	255	255.0	257.0	258.0	258.0	257.0
Amperes		327.5	665.0	955.0	1303.0	1347.0
Kw		86.1	170.8	246.6	336.1	346.0
B.h.p.		129.6	247.6	356.5	489.3	503.0
Per cent full rating		25.9	49.5	71.2	97.9	100.5
Speed drop, per cent ± mean		0.819	0.958	1.597	1.916	2.236

Instantaneous Load Test June 27, 1907, 6 p.m.

No-load to full-load, 280 volts, 1190 amperes, 345 kilowatts, 502 brake horse power.
No-load speed .... 155 revolutions per minute.
Load thrown on .... 148 revolutions per minute.
Load thrown off .... 155 revolutions per minute.
Difference .... 7 revolutions per minute.
Speed variation ....4.6 per cent of total − 2.3 per cent ± mean speed

RESULTS OF TESTS.

The following data has been taken from actual tests made on a number of power stations in which gas engines are installed, such as:

The Citizens' Electric Company, Keene, N. H.

The Norton Company, Worcester, Mass.

American Locomotive Company, Richmond, Va.

Philadelphia High Pressure Pumping Station, Philadelphia.

Warren and Jamestown Street Railway Company, Stoneham, Pa.

These tests show an average coal consumption of 1.29 pounds per brake horse power hour, and an average thermal efficiency of 19.2%. They show that from full load to one quarter load, the coal consumption increased only 26%, and that the maximum coal consumption in this range, which, of course, occured at one quarter load, was only 1.7 pounds per brake horse power hour.

TABLE III

AVERAGE OPERATING EFFICIENCY—GAS-POWER CENTRAL STATION

CITIZENS' ELECTRIC COMPANY, KEENE, N. H.

Station capacity (three units)	270 kilowatts
Number of months run	8.5
Average station load-factor	19.7 per cent
" load on unit (per cent rating)	50.9 " "
Total coal per kilowatt-hour	2.94 pounds
" " " b.h.p.-hour	1.86 "
Coal gasified per kilowatt-hour	2.3 "
" " " b.h.p.-hour	1.45 "
Approximate calorific value of coal	12,500 B. t. u.
Heat consumption, net per kilowatt-hour	28,680 "
Absolute net heat efficiency from coal pile to switchboard	11.9 per cent

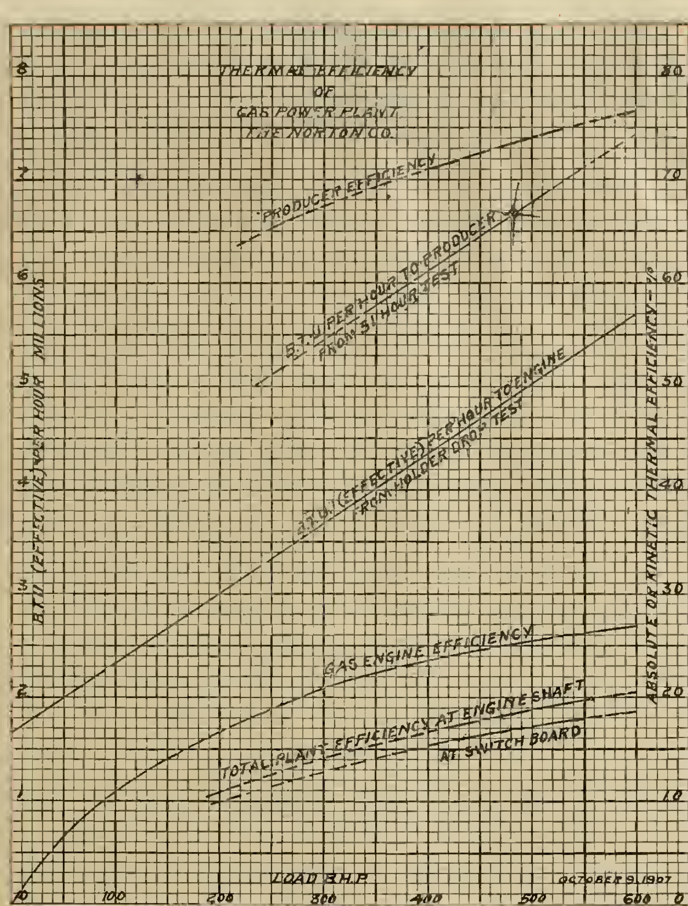


FIG. 8 THERMAL EFFICIENCY OF GAS POWER PLANT

TABLE NO. 8 NORMAL OPERATING ECONOMY

NORTON GAS POWER PLANT

AVERAGE FOR NINE WEEKS ENDING APRIL 21, 1907

Number of hours per week run on load	54.4	hours.
Output	13 500.0	kw-hrs.
Average running load	248.1	kw.
Average running load per cent rating of engine	72.2	per cent
Coal gasified (including standby losses)	24 839.0	pounds
Coal for new fires	2 369.0	pounds
Coal for new fires (per cent of producer coal)	9.5	per cent
Total coal for all purposes	27 204.0	pounds
Avg. total coal per hour including new fires	500.00	pounds
Coal consumed (excluding new fires) per kw-hr	1.83	pounds
Total coal consumed per kw	2.015	pounds

TABLE V

Operating Costs—Gas-Power Railway Plant

WARREN AND JAMESTOWN STREET RAILWAY COMPANY

Capacity of plant (two units) .... 600 kilowatts
Average time operated per day .... 18.5 hours
" output per day .... 4115 kilowatt-hours
" load—per cent rating .... 37 per cent

Cost of Power	Dollars per Day	Cents per Kilowatt-Hour
Average First Four Months, 1906:		
Fuel gas	12.97	0.315
Wages	12.37	0.300
Oil	2.63	0.064
Repairs and miscellaneous supplies	3.29	0.080
Total	31.26	0.759

Fuel—"Bradford Sand" natural gas.

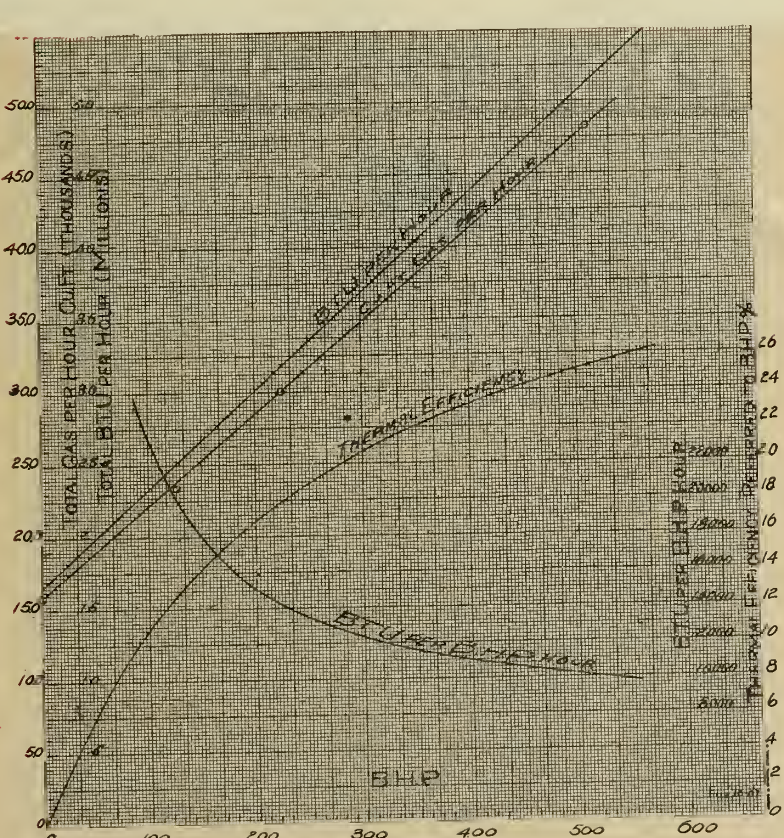


FIG. 2
Test of a 500 Horse Power Westinghouse Gas Engine

STEAM TURBINES VERSUS GAS ENGINES AS PRIME MOVERS.

From all the data which has been given regarding plants equipped with either of these types of prime movers, a comparison will be drawn in order to determine which type is better adapted for the plant under consideration.

COAL CONSUMPTION.

Average values taken from curves and tables which accompany this thesis show:

Gas Engine	Steam Turbine
1.29 pounds per B. H. P. hour.	2 pounds per B. H. P. hour

FLOOR SPACE.

Gas Engine Plant	Steam Turbine Plant
6.25 sq. ft. per K. W.	2.39 sq. ft. per K. W.

COMPARISON OF OPERATING EXPENSES.

Gas Engine Plant

First cost at $138 per kilowatt	$82800.00
Interest @ 5%	4140.00
Insurance and taxes 1.5%	1240.00
Depreciation(sinking fund 15 years @ 5%) 4.63%	3840.00
Repairs 1.5%	1240.00
Total	$10460.00
Coal per year - 1250 tons @ $1.23	1540.00

Assume labor and supplies same as that for steam turbine plant.

Total yearly operating expenses plus fixed charges $12000.00

Steam Turbine Plant

First cost @ $100 per kilowatt	$60000.00
Interest @ 5%	3000.00
Insurance and taxes-1.5%	900.00
Depreciation(sinking fund 16 2/3 years 5%) 4%	2400.00
Repairs - 1.5%	900.00
Total	$6900.00
Coal per year - 1905 tons @ $1.23	2345.00

Assume labor and supplies same as that for gas engine plant.

Total yearly operating expenses plus fixed charges $9245.00

This comparison of costs of power is based on the costs of the 700 kilowatt Gas Power Plant of the American Locomotive Company, Richmond, Va. The data given in the first table below was compiled by Mr. J. R. Bibbins; that in the second table, by the Du Bois Gas Engine Company.

Equipment cost:
Building and machinery $96,600
Cost per kilowatt, $138, per brake h.p., $96.60.
Fixed charges:
Interest 5%, taxes and insurance 1.5%, depreciation (sinking fund 15 years 5%), 4.63%, running repairs 1.5% on investment. Total 12.63% per year 12,220
Operation:
300 days, 7200 hr. per year, 5,040,000 kw-hr.
Input to auxiliaries, 5.4% full, 10.8% half-load.
Standby losses, producer plant, 1600 lb. per week, 2.1% full, 3.1% half-load.
Fuel rate, full load, 1.59 lb. + 2.1% = 1.62 lb. per kw-hr.; ½-load 2.1 lb. + 3.1% = 2.17 lb. per kw-hr.

COST OF POWER, 700-KW. TURBINE PLANT.
ASSUMPTIONS.

Equipment:
Building and machinery, $100 per kilowatt $70,000
Fixed charges:
Interest 5%, taxes and insurance 1.5%; depreciation (sinking fund 16⅔ yrs. at 5%) 4%; repairs 1%; total 11.5% 8,050
Operation:
300-day year, 7200 hr.
Average water rate, full-load 21.5 lb. per kw-hr.
Average water rate, one-half load 25.5 lb. per kw-hr.
Gross evaporation, 7.5 to 8.0 lb.
Standby, banking, 10 to 15%.
Gross coal consumption, full, 2.96 lb. per kw-hr.; half, 3.9 lb. per kw-hr.
Wages and supplies—Same as gas.

STEAM POWER PLANT vs. GAS PRODUCER POWER PLANT

	Steam	Gas Producer
Rated H. P. of plant	200 H. P.	200 H. P.
Type of Plant	Tubular boilers, non-condensing steam engine.	Suction Gas Producer and DuBois Throttling Gas Engine.
Load factor	10 hrs. full load, 14 hrs. idle.	10 hrs. full load, 14 hrs. idle.
Fuel, kind, price, quantity	Bituminous coal @ $2.75 per ton; 6 lbs. per H. P. H., full load; 3 lbs. per H. P. for 14 hr. stand-by loss.	Anthracite @ $4.50 per ton; 1 lb. per H. P. H., full load; .57 lbs. per H. P. for 14 hrs. stand-by loss.
Amount of oil, price	2 gal. per H. P. year @ $ .30 per gal.	3 gals. per H. P. year @ $ .30 per gal.
Amount of waste, price	500 lbs. per year @ $ .07 per lb.	600 lbs. per year @ $ .07 per lb.
Amount of water, price	3600 M gal. @ $ .03, based on 8 lbs. evaporation per lb. coal.	7200 M gals. @ $ .03 per M.
Labor	Engineer @ $3.00 per day. Fireman @ 1.75 per day. Night attention @ $1.00 per day. Total, $5.75 per day.	Engineer @ $3.00 per day. Assistant 4 hrs. @ $ .15 per hr. No night attention required. Total, $3.60 per day.

SUMMARY

STEAM

Cost of Coal	1890 tons	@	$2.75	$5197.50
Oil	400 gal.	@	.30	120.00
Waste	500 lbs.	@	.07	35.00
Water	3600 M gal.	@	.03	108.00
Labor	300 days	@	5.75	1725.00
Total operating expense for H. P. year of 3000 working hours				$7185.50
Approximate first cost of plant, including foundation, erection, etc.				7200.00
Operating expenses				1785.50
Interest at 5% on first cost				360.00
Depreciation 6%				432.00
Repairs 2%				144.00
Total yearly expenses				$8121.50
Saving in first cost in favor of steam plant				1800.00

PRODUCER GAS

Cost of Coal	317 tons	@	$4.50	$1427.00
Oil	600 gal.	@	.30	180.00
Waste	600 lbs.	@	.07	42.00
Water	7200 M gal.	@	.03	216.00
Labor	300 days	@	3.60	1080.00
Total operating expense for H. P. year of 3000 working hours				$2945.00
Approximate first cost of plant, including foundation, erection, etc.				9000.00
Operating expenses				2945.00
Interest at 6%				540.00
Depreciation 8%				720.00
Repairs 2%				180.00
Total yearly expenses				$4385.00
Annual saving in favor of gas power plant				3736.50

THE ABOVE TABLE HAS BEEN CAREFULLY AND CONSERVATIVELY COMPILED FROM DATA GATHERED IN ACTUAL PRACTICE FROM PRODUCER GAS AND STEAM PLANTS

[illegible]	810	15.45	*0.73	†.30	.58	.10	1.71

*Cost of coal, $6.50 to $6.75 per ton. †Water purchased — artesian well not yet in service.
¶Repairs include repairs to buildings, batteries and distribution system.

CONCLUSION.

From the comparison given above, it is seen that the first cost and fixed charges are both greater in case of the gas engine plant; that the coal consumption is less in the gas engine plant; and therefore, that the price of coal is the principal factor which determines the type of plant for the better economy. It is also seen that the price of coal in this case is low enough to favor the steam turbine plant.

Therefore, in view of the fact that the steam turbine has the advantage over the gas engine in points of simplicity, ability to carry overload, size, and uniform torque, as well as in economy, it is decided to install steam turbines.

CHOICE OF UNITS.

The units are to be two phase, four hundred and forty volt, sixty cycle, direct connected turbo-generators. The conditions of voltage and frequency are fixed by the systems of wiring and the apparatus already in use in the buildings and laboratories.

After considering all the data and information that could be obtained concerning turbines, it was decided to design the plant for Westinghouse Parsons Turbines. This decision was made partly because we believe the Parsons turbine to be more applicable to units of this size, and partly because much more information regarding tests and dimensions of small units, was furnished.

The exciter units necessary for this installation, allowing 4% of the total capacity of the plant, will be twenty five kilowatt, one hundred and ten volt, direct current generators, direct connected to De Laval turbines. It is believed that the De Laval turbines will drive the exciters satisfactorily.

To insure continuity of service, two exciter units should be installed, one being held in reserve.

It is necessary to provide some source of direct current, so a motor generator set of seventy five kilowatts capacity, which is considered sufficient for any direct current load that may be expected, will be installed. The motor will consist of a two phase, four hundred and fourty volt, seventy five kilowatt synchronous motor. The generator will be a two hundred and twenty volt three wire machine.

If the present system of arc lighting for the campus were used, it would be necessary to use a special direct current light machine. In order to avoid the necessity of an additional unit, it is thought advisable to abandon this system and install alternating current lamps with a constant current transformer.

FUEL CONSUMPTION.

Data - Boiler Pressure 150#

Feed Water Temperature 200 degrees.

Superheat 100 degrees.

Boiler Efficiency 65% (assumed).

Steam consumption for turbines 15 lbs. per B.H.P. hr.

Taken from tests on Westinghouse Parsons Turbines.

Steam consumption for exciters 15 lbs. per B.H.P. hr.

Allowance for other auxiliaries 6%

Generator Efficiency 90% (assumed).

600 K.W. = 805 H.P. 805/.90 = 895 H.P. Capacity of turbines.

895 x 15 = 13400 lbs. steam per hour for turbines.

35 x 15 = 525 lbs. steam per hour for exciters.

Adding 6% 835 lbs. steam per hour for other auxiliaries.

14760 lbs. steam per hour, total.

Heat in liquid at 200 degrees - - - -	168.2	B.T.U. per lb.
Heat in steam at 150# pressure - - - -	1194.2	" " "
Heat added by superheat - - - - -	48.0	" " "
Heat to be supplied per lb. of water	1074.0	B.T.U.

14760 x 1074 = 15800000 B.T.U. per hour in steam.

15800000/.65 = 24350000 B.T.U. per hour in coal.

Illinois coal contains 13125 B.T.U. per lb.

24350000/13125 = 1850 lbs. coal per hour when running at full load.

MECHANICAL STOKERS.

Mechanical stokers are money savers only when the interest and depreciation on first cost plus the cost of attendance minus the saving in coal consumption is less than the cost of firing by hand. In a plant of this size it would require about as much labor to care for the stokers as would be required to fire the boilers by hand, to say nothing of the interest and depreciation on the stokers. Therefore, it is not advisable to install mechanical stokers.

COAL STORAGE.

In view of the fact that a coal strike might result in the shutting down of the plant for want of coal, it is desirable to provide storage for about thirty days. It is estimated from the coal consumption when running at full load, that the plant will use about ten tons of coal per day. This means a storage for three hundred tons. One ton of coal takes up about forty five cubic feet. (Herrick Handbook).

The boiler room is sixty feet wide, so a space of the following dimensions will suffice: 60 X 12 X 15 or 10800 cubic feet. This gives storage for two hundred and forty tons.

CONSIDERATION OF SUPERHEATED STEAM AND CONDENSER PRESSURE.

Experience has shown that the use of 100 degrees superheat and a 28 inch vacuum in the condenser give best results for practical operating conditions.

BOILERS.

The Babcock & Wilcox water tube boilers were chosen for the following reasons.

(1) They are highly efficient.

(2) They require small space per boiler horse power.

(3) They may have the superheater placed within the boiler itself and the heat for superheating is taken from the hot gases in the boiler. Thus no separate furnace is required for superheating.

The total boiler horse power from the heat consumption of 15800000 B.T.U. per hour is 475 B.H.P.

It is advisable to install three two hundred horse power boilers equipped with superheaters. This boiler capacity will allow for increase in output and also make it possible to shut down any one of the boilers without overloading the other two to any great extent.

The boiler room has been designed using the dimensions furnished by the Babcock & Wilcox Company.

BOILER FEED PUMPS.

Three boiler feed pumps, each of twelve gallons per minute capacity, are deemed necessary in order that a certain and flexible control of feed water may be had.

Pounds of water handled per minute - 224 pounds

Three pumps will handle 75 pounds per minute.

Therefore, allowing about 20% for results of wear, slip, and leakage, it will require three 12 gallon pumps.

STEAM PIPES.

The sizes of steam pipes were calculated by the method given in Herrick's Handbook.

Pipe	Size
Boiler to header	3 inch
Header	4 inch
Header to 250 K. W. Unit #1	3 inch
Header to 250 K. W. Unit #2	3 inch
Header to 100 K. W. Unit and exciter turbines	2 inch
Exhaust from turbine to condenser(250 K. W. Unit)	6 inch
Exhaust from turbine to condenser(100 K. W. Unit)	4 inch

The sizes of the auxilary live and exhaust steam pipes were taken from bulletins from which the auxilaries were chosen.

WATER PIPES.

The sizes of water pipes were taken from the bulletins from which the pumps were chosen. The water pipes have been omitted from the drawings for the sake of clearness of the drawing.

HOT WELL.

The hot well was designed to hold the condensate of a one hour's run at full load. The tank is to have a capacity of 1000 gallons,and is to have the following dimensions:

Diameter - 5 feet

Height - 6.8 feet

It is to be placed 6 feet above the boiler room floor in order that the water will run by gravity into the heater.

DESIGN OF STACK.

A stack eighty feet high will tower above any trees or buildings in the immediate vicinity.

The area of cross section can be found by the use of Kent's formula:

$$A = \frac{.06 \times W}{\sqrt{H}}$$

where W is the pounds of coal burned per hour, H is the height of the stack in feet and A is the area of the cross section in square feet.

This gives as a result,

$$A = 12.3 \text{ sq.ft.}$$

A circular stack, 4 feet in diameter, will be sufficient to allow for friction losses and slight increases in the coal consumption.

The area of the cross section of the flues is to be about 25% less than the area of the cross section of the stack.

CONDENSERS.

Surface condensers were chosen as best adapted for turbine work. Allowing four square feet of cooling surface per kilowatt capacity of the plant, the total number of square feet surface required is twenty six hundred ~~thousand~~. This is divided among three condensers as follows:

# 1	for	250	K.W.	unit	- - -	1000	sq.ft.
# 2	"	250	"	"	- - -	1000	"
# 3	"	100	"	"	- - -	600	"

The vacuum and circulating pumps for the condenser service are direct connected to the condenser.

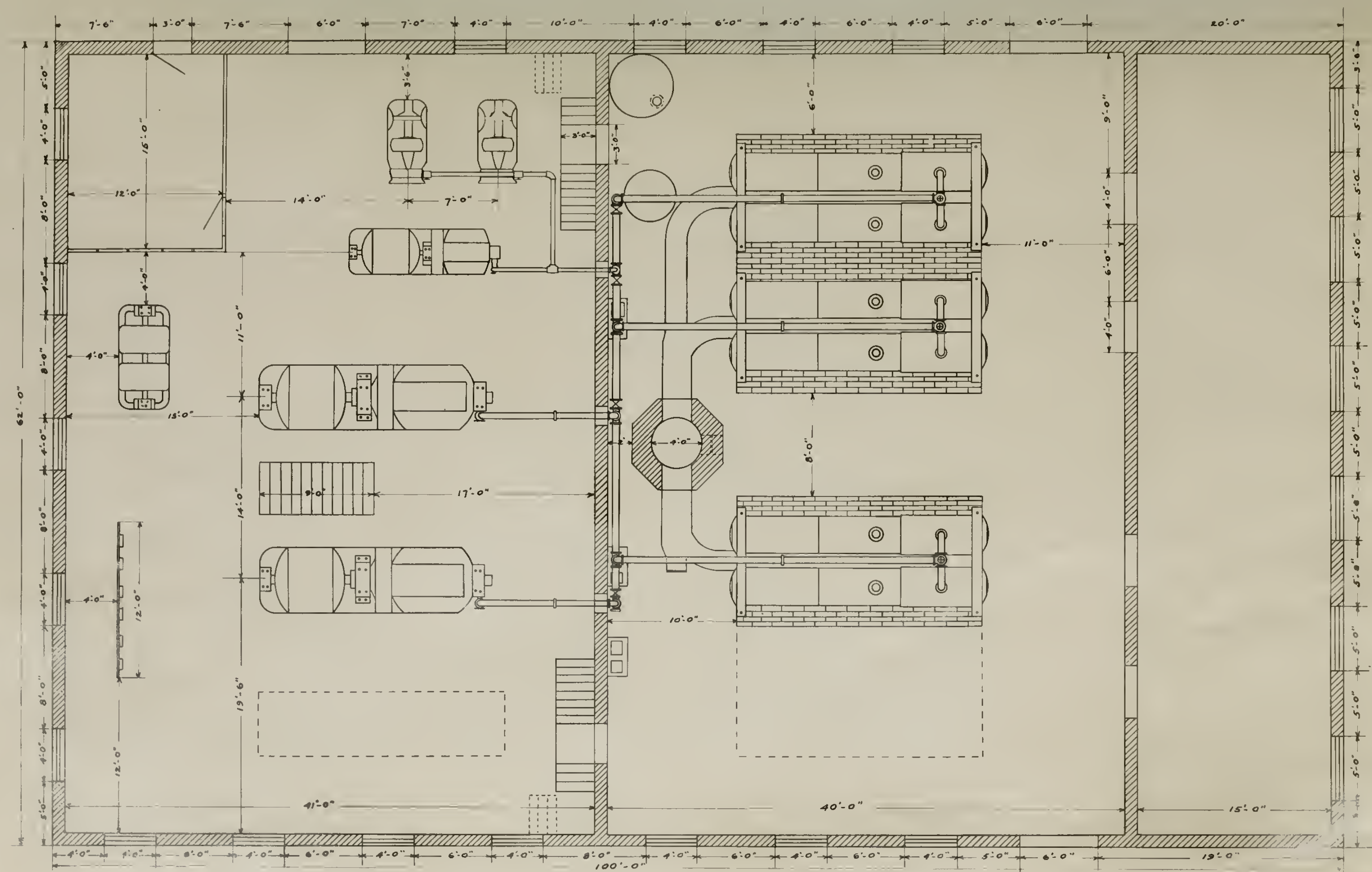
FEED WATER HEATER.

One open heater of five hundred horse power capacity is provided for to utilize the heat of the exhaust steam from the auxiliaries. For the sake of calculation, it is assumed that ten percent of the total steam is required for the auxilaries.

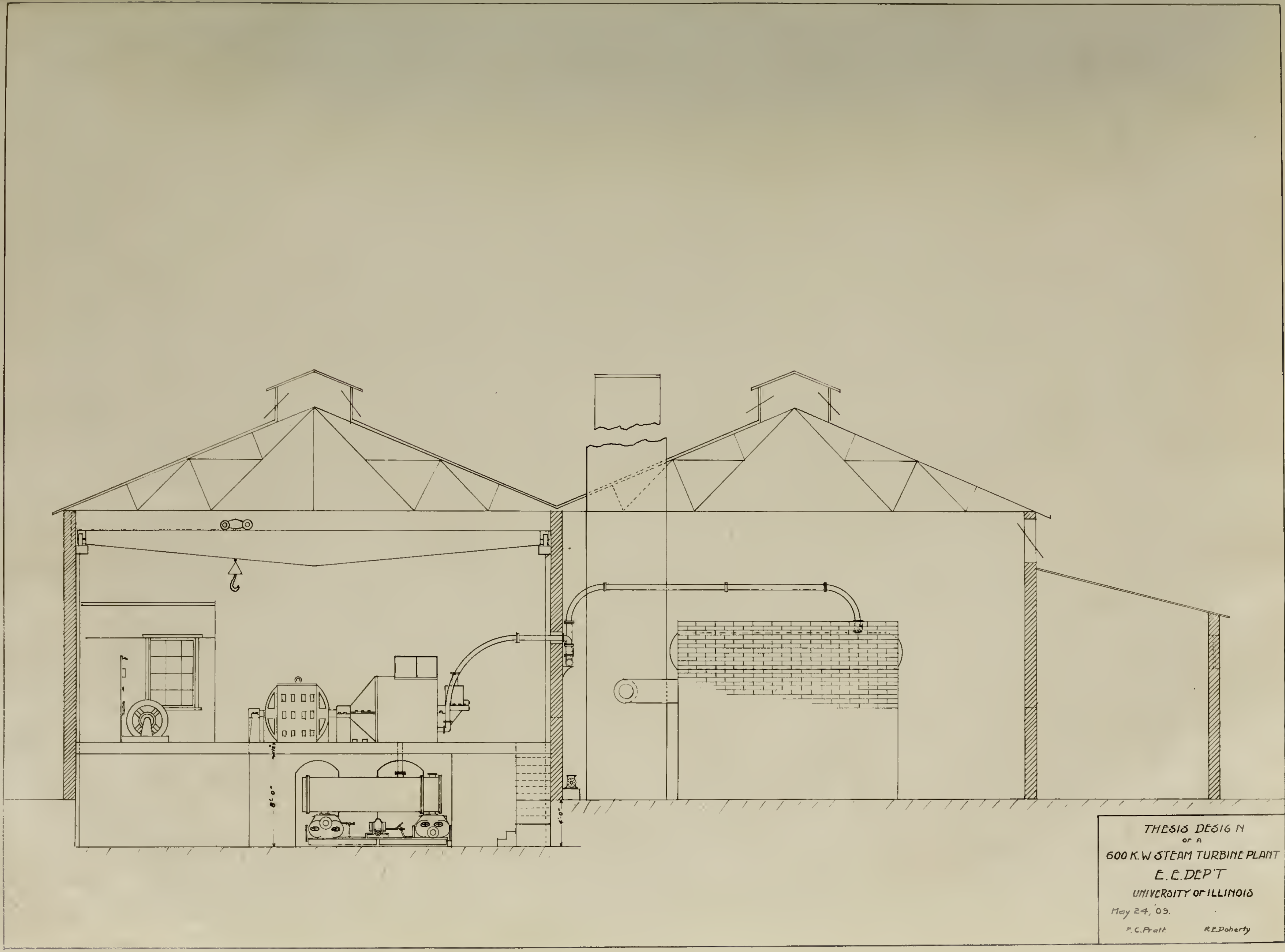
One pound of steam from the auxilaries will be at atmospheric pressure, and will contain about 900 B. T. U. of latent heat. One pound of condensate at 130 degrees contains 98 B. T. U. Therefore, it will require 70 B. T. U. to heat each pound of condensate up to 200 degrees. Since each pound of auxilary exhaust has to heat only nine pounds of feed water, it is seen that the nine pounds will be increased in temperature by 100 degrees, that is 900/ 9. This gives an allowance of thirty percent for loss of heat by radiation, discharge, and the addition of new supply water.

DRAWINGS.

The plates given on the following pages show the plan and section of the plant which has been designed to fulfill the power requirements of the University of Illinois as outlined on pages 2 and 3 of this thesis.



THESIS DESIGN
OF A
600 K W STEAM TURBINE PLANT
E E DEP'T
UNIVERSITY OF ILLINOIS
May 24. 09
RE Doherty



4'-0"
8'-0"
THESIS DESIGN
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P. C. Pratt
R. E. Doherty

BIBLIOGRAPHY OF REFERENCES

Industrial Progress March, 1909.

"Some theoretical and practical considerations of steam turbines", a paper presented before the A. S. M. E. by F. Hodgkinson.

Bulletin number 15 of the Model Gas Engine Works, Peru, Indiana.

"Duty test on a gas engine plant", a paper read before the A.S.M.E. by Mr. G. I. Alden.

"Working results of a gas-electric power plant", a paper read before the A.I.E.E. by Mr. J. R. Bibbins.

Bulletin number 4 of the Otto Gas Engine Works, Philadelphia, Pa.

Bulletin of the Dubois Gas Engine and Iron Works, Du Bois, Pa.

Bulletin on the Westinghouse Steam Turbine, Westinghouse Company of East Pittsburg, Pa.

"The turbo-electric drive in paper mill service", Engineering Record, September 2, 1905.

"Recent developments in steam turbine power station work", a paper read before the A.S.and I.E.A. by J. R. Bibbins.

"Turbine power station" Engineering Record, June 10, 1906.

"Steam-electric power plants" Koester